

# Standard Model and New Physics: theoretical and experimental perspectives<sup>(\*)</sup>

A. CASTRO<sup>(1)</sup> and G. CORCELLA<sup>(2)(3)</sup>

<sup>(1)</sup> *Università di Bologna and INFN, Sezione di Bologna, Italy*

<sup>(2)</sup> *Museo Storico della Fisica e Centro Studi e Ricerche E. Fermi, Roma, Italy*

<sup>(3)</sup> *Scuola Normale Superiore and INFN, Sezione di Pisa, Italy*

**Summary.** — In this summary we present the current status of the Standard Model of strong and electroweak interactions from the theoretical and experimental point of view. Some discussion is also devoted to the exploration of possible New Physics signals beyond the Standard Model.

PACS 12.15.-y – Electroweak interactions.

PACS 12.38.-t – Quantum Chromodynamics.

PACS 12.60.-i – Models beyond the Standard Model.

## 1. – Introduction

The Standard Model is the theory of strong and electroweak interactions: they are described in terms of quarks and leptons, the basic constituents of matter, and gauge bosons, which are the carriers of the fundamental forces. This model is kept endlessly under inspection by comparing measured observables, such as couplings, masses, integral and differential cross sections or branching ratios, with the theory expectations.

The interplay between theory, which is continuously improving its predictions, and experiments, whose measurements are carried out with increasing accuracy, consolidates the Standard Model itself. At the same time, however, the Standard Model presents some drawbacks which open the road to New Physics; the forthcoming experiments at the Large Hadron Collider will provide us with a unique chance to address these open problems.

We present in the following our perspective, from both theoretical and experimental viewpoints, on the current situation of the Standard Model and discuss some of its open issues, which call for New Physics extensions.

---

(\*) Summary talk at ‘Incontri di Fisica delle Alte Energie’, Bologna, Italy, 26 – 28 March, 2008.

## 2. – Theoretical and phenomenological issues

Quantum Chromodynamics (QCD), an unbroken renormalizable theory based on the colour  $SU(3)$  gauge symmetry, is a main part of the Standard Model of particle physics, as it is the theory of strong interactions. At present and future colliders, having full control of QCD is fundamental, since events mediated by the strong interaction may mimic New Physics signals.

Because of asymptotic freedom, at high energies QCD observables can be computed as fixed-order expansions in the coupling constant  $\alpha_S(Q^2)$  (perturbative QCD). Most cross sections have been computed at next-to-leading order (NLO), whereas a few have been provided with next-to-next-to-leading order (NNLO) corrections as well. In fact, as NLO corrections can be as large as a factor of two, leading-order (LO) results can just estimate the order of magnitude of an observable, with the NLO giving the first reliable prediction. NNLO computations are nonetheless still necessary to reduce the theoretical uncertainty and weaken the dependence, *e.g.*, on the choice of parton distributions or fragmentation functions.

Among recent NLO calculations, we can mention the corrections to the production of three vector bosons at the LHC, namely  $ZZZ$ ,  $WZZ$ ,  $WWZ$  and  $WWW$ : the results on the transverse momentum ( $p_T$ ) spectrum show that the NLO has a relevant impact, indeed up to a factor of two, at small  $p_T$  [1].

While fixed-order calculations are reliable enough to predict inclusive observables, such as total cross sections and widths, differential distributions can exhibit contributions where  $\alpha_S(Q^2)$  is multiplied by logarithmic coefficients, which become large for soft or collinear parton radiation. Resumming such terms is mandatory to describe exclusive quantities.

A remarkable example, where the interplay between fixed-order and resummed computation is crucial, is Higgs-boson production in the  $gg \rightarrow H$  channel, the dominant one at the LHC. The Higgs rapidity and transverse momentum spectra have been computed to NNLO accuracy; moreover, the logarithms  $\ln(p_T^2/m_H^2)$ , large at small  $p_T$ , where one is mostly sensitive to soft and collinear emissions, have been resummed in the next-to-next-to-leading logarithmic (NNLL) approximation and included in the Monte Carlo code HqT [2].

At low energy, however, one is faced with non-perturbative power corrections which cannot be calculated in perturbative QCD. In fact, one may address non-perturbative phenomena, such as hadronisation or underlying event, following several models and approaches, which are typically based on fits to experimental data. As far as hadronisation is concerned, an alternative possibility consists in defining an effective strong coupling constant, free from the Landau pole, which at large energy coincides with the standard coupling and at small energy includes non-perturbative power corrections. Studies have shown that the effective-coupling model, used along with a resummed calculation in the framework of perturbative fragmentation functions, yields a reasonable description of data on  $b$ - and  $c$ -flavoured hadrons at LEP and SLD, without tuning any parameter to such data [3].

Another approach to non-perturbative QCD parametrises low-energy physics by means of the frozen coupling constant, defined as the integral of  $\alpha_S(p_T^2)$ , where  $p_T$  is some transverse momentum characteristic of the process, from zero to an upper limit, fitted to experimental data. In this way, one can, *e.g.*, study jet observables at the Tevatron or the LHC, obtaining results in reasonable agreement with Monte Carlo generators, such as HERWIG or PYTHIA, which implement their own models for hadronisation and

underlying event, tuned to LEP or Tevatron data [4].

Along with the intensive applications of QCD to collider phenomenology, work has been lately undertaken to construct a dual model of QCD, in the fashion of the AdS/CFT correspondence. In the framework of such a model, called holographic QCD, one can perform a linear fit of the experimental spectrum of  $\rho$  mesons and give predictions for masses and decay constants of the  $0^{++}$  glueballs [5].

The electroweak sector of the Standard Model is based on a  $SU(2)_L \times U(1)_Y$  symmetry, spontaneously broken into  $U(1)_{\text{em}}$ . Although the electroweak theory has been successfully tested in several experimental environments, the Higgs boson, a crucial ingredient of the model, as it is responsible of the mass generation mechanism, has not been discovered yet. There are, however, indications that a mass mechanism in the fashion of the Higgs one should exist: for instance, the observed longitudinal polarisations of  $W$  and  $Z$  bosons are indeed manifestations of a broken symmetry. Furthermore, the relation between their masses, namely  $M_W^2 = M_Z^2 \cos^2 \theta_W$ ,  $\theta_W$  being the Weinberg angle, valid up to very small radiative corrections, confirms the so-called custodial  $SU(2)$  symmetry of the Standard Model and that the Higgs boson has to be a weak-isospin doublet.

The LHC has been designed to solve the Higgs problem, as it will be able to search for a Standard Model Higgs boson, with a mass up to  $m_H \simeq 1 \text{ TeV}/c^2$ . On the theory side, the lack of the Higgs discovery has opened the road to other scenarios beyond the Standard Model, including the possibility that the Higgs may not exist (Higgsless models) or that it is an approximate Goldstone boson of a broken global symmetry (composite Higgs models). Also, conceptual drawbacks, and especially the well-known hierarchy problem, namely the quadratical divergence of the Higgs mass after radiative corrections, requiring fine tuning of several orders of magnitude, call for extensions of the Standard Model. Among these, one of the most appealing and widely studied is surely supersymmetry, with its minimal formulation, the Minimal Supersymmetric Standard Model (MSSM).

Calculations and computing codes implementing supersymmetric processes have been available for a few years. Work has been lately carried out to provide such computations with radiative corrections, which are likely to have a remarkable impact at the LHC, and must be taken into account in any reliable analysis. An example is given by the inclusion of NLO electroweak corrections to squark-antisquark pair production at hadron colliders, included in the Monte Carlo program PROSPINO [6].

A common feature of several New Physics models is that they predict the existence of new heavy vector bosons  $Z'$ . Indeed,  $Z'$  production in Drell–Yan type processes, followed by leptonic decays, are among the first New Physics signals possibly visible at the LHC. Ref. [7] discusses  $Z'$  production in the so-called left-right symmetric free-fermionic model, which enlarges the gauge structure of the Standard Model by an extra heterotic-string inspired  $U(1)$  (see [7] for more details). The free-fermionic model is constructed in such a way to suppress proton decay; moreover, it is anomaly-free and consistent with the see-saw mechanism for neutrino masses, with family universality and Yukawa-like couplings. Within this model,  $Z'$ -production processes have been provided with QCD corrections to NNLO accuracy and should be visible at the LHC in the channels  $Z' \rightarrow \gamma\gamma$  and  $Z' \rightarrow ZZ \rightarrow \ell_1 \bar{\ell}_1 \ell_2 \bar{\ell}_2$ .

Although the electroweak precision tests seem to favour a possibly light Higgs, as will be discussed in detail in the next section, it is nonetheless still possible to accommodate a heavy Higgs beyond the Standard Model, since New Physics effects can contribute to electroweak observables and make a heavy Higgs consistent with present data. An example is the so-called  $\lambda$ SUSY model, based on an extension of the MSSM, which predicts

the existence of a heavy Higgs  $H$ , with mass, *e.g.*, 500-600 GeV/ $c^2$ , mainly decaying, via  $H \rightarrow hh$ , into a pair of lighter Higgses  $h$ , having mass  $m_h \simeq 200\text{-}300$  GeV/ $c^2$ . The properties of the lighter Higgs  $h$  are supposed to be pretty similar to the Standard Model one. In fact, New Physics contributions, *e.g.* to the oblique parameters  $S$  and  $T$ , make  $\lambda$ SUSY still compatible with the constraints of the electroweak precision tests, which do seem to favour a rather light Higgs, but only within the Standard Model and without assuming any New Physics effect [8]. The  $\lambda$ SUSY model is expected to be possibly observable at the LHC with 100 fb $^{-1}$  of integrated luminosity.

Nevertheless, a possible alternative is to try to describe the electroweak interactions and solve the hierarchy problem in the framework of the so-called Higgsless models. A process which has been thoroughly investigated is  $WW$  scattering: in the Standard Model, the exchange of an intermediate  $H$  moderates the growth of the cross section for longitudinal boson scattering, and the requirement of unitarity sets the limit  $m_H < 1$  TeV/ $c^2$  on the Higgs mass. In Higgsless models, the starting point is typically a  $SU(2)_L \times SU(2)_R$  chiral symmetry, spontaneously broken to  $SU(2)_{L+R}$ : in this way, one or more new heavy vector bosons replace the Higgs and delay the unitarity issue to a few TeV/ $c^2$ .

Ref. [9] discusses the four-site Higgsless model, which presents four new vector bosons, *i.e.* two charged  $W_{1,2}^\pm$  and two neutral  $Z_{1,2}$ . At the LHC,  $W'$  and  $Z'$  bosons can be produced in Drell–Yan like processes, thus giving rise to visible resonances. Thanks to these new gauge bosons, the problem of unitarity violation is delayed to energy scales which are much higher than those actually probed at the LHC. Unlike other Higgsless models, such vector bosons are not ‘fermiophobic’, as the electroweak precision data do allow sizeable couplings with fermions.

Before closing this section, we point out that, for the sake of experimental analyses, any New Physics model needs to be implemented in Monte Carlo generators, in order to account for multiple initial- and final-state radiation, hadronisation and underlying event. In fact, work towards this direction has seen tremendous improvements in the latest few years. As for  $WW$  scattering, it is worthwhile to mention the PHANTOM code, which implements final states with six fermions, and includes the option of no intermediate Higgs boson as well. By using PHANTOM, it will be possible to study  $WW$  scattering at the LHC and, in the phase of 100 fb $^{-1}$  luminosity, discriminate between, *e.g.*, a Standard Model scenario with a Higgs of mass  $m_H \simeq 200$  GeV/ $c^2$  and the no-Higgs case [10].

### 3. – The experimental status

The Standard Model continues to be explored in different experiments based on accelerators or not. The Tevatron, colliding beams of protons and antiprotons with the currently highest energy of  $\sqrt{s} = 2$  TeV, represents a very favourable environment where to perform an extensive study of the major ingredients of the Standard Model, *i.e.* quarks and gauge bosons. Figure 1 shows, as an example, the production cross section at the Tevatron for different categories of processes: the production of  $b$ -hadrons,  $W$  and  $Z$  bosons, events containing the top quark, and finally the possible production of the Higgs boson. These and other processes are thoroughly studied by the two multi-purpose experiments operating at the Tevatron, namely CDF and DØ.

Given the cross sections and the current integrated luminosity (about 3 fb $^{-1}$ ), the production of events containing  $W$  or  $Z$  bosons is large, of the order of a few hundred thousand events. Also, even if the Tevatron cannot be really considered a top factory,

the production of top quarks is quite abundant, with yields, so far, of about  $2 \times 10^4$   $t\bar{t}$  pairs and about  $6 \times 10^3$  single-top events per year. On the other hand, the production of the Higgs boson is expected to be very rare at the Tevatron and only the total integrated luminosity before the final shutdown, which is foreseen to be about  $6\text{--}8 \text{ fb}^{-1}$ , along with a full exploration and combination of all possible channels, might enable to obtain some results.

The situation taking place at the Tevatron will change drastically once the LHC, colliding beams of protons with  $\sqrt{s} = 14 \text{ TeV}$ , reaches its full power. The production cross sections at LHC will increase, with respect to the Tevatron ones, by one order of magnitude for  $W/Z$  production and by two orders for top production. This, along with the higher-design instantaneous luminosity, will make LHC a real top-factory, and a promising environment for Higgs discovery.

Given the different yields of the processes described in Figure 1, it is suitable to divide the experimental studies of the major Standard Model processes into three subfields:  $W/Z$  physics, production of top quarks and searches for the Standard Model Higgs boson. In addition, we shall briefly discuss the exploration for New Physics beyond the Standard Model.

**3'1.  $W/Z$  physics.** – The study of the  $W/Z$  boson production, within the Standard Model, is crucial because it can provide accurate tests of both electroweak and strong interactions; QCD corrections to the production cross section are in fact available in the NNLO approximation.

CDF and DØ typically measure [11] the production cross sections for leptonic final states, *i.e.*  $\sigma_W \times BR(W \rightarrow \ell\nu)$  and  $\sigma_Z \times BR(Z \rightarrow \ell^+\ell^-)$ , along with their ratio and the  $W$ -width  $\Gamma_W$ . The size of the samples also enables the study of differential distributions.

The measurement of the  $W$  mass is very important, due to its link through radiative electroweak corrections to the Higgs boson mass. The mass is measured at the Tevatron using the large sample of inclusive  $W$  events, where the  $W$  decays into  $e\nu$  or  $\mu\nu$ . The  $W$  transverse mass,  $M_W^T = \sqrt{2P_T^\ell P_T^\nu(1 - \cos \Delta\Phi^{\ell\nu})}$ , is reconstructed using the missing transverse energy, as a measure of  $P_T^\nu$ , measuring the azimuthal angle  $\Delta\Phi^{\ell\nu}$  between the lepton and the direction of the missing transverse energy, and is finally fitted to the expected distributions for different values of the  $W$  mass. This measurement is a very delicate one, because it relies on a very precise calibration of the lepton momenta, and even the underlying event and additional  $p\bar{p}$  interactions must be taken into account. With this technique, and using only 1/15 of the luminosity currently available, CDF already reaches an accuracy better than what was measured by the various experiments at LEP, thus improving the world average.

The study of diboson production  $WW$ ,  $WZ$  and  $ZZ$  is accessible in spite of the relatively low production cross sections (respectively about 10, 4 and 1 pb). The investigation of these events is quite interesting not only in itself, but also because they represent relatively rare processes, with topologies similar to what can be expected for Higgs boson production. In fact,  $WZ$  production has been clearly observed and there are first hints of  $ZZ$  evidence.

At the LHC, given the high energy and luminosity, a large number of  $W$  and  $Z$  events will be collected shortly after the machine turn-on, with a very clean leptonic signature. Even before providing accurate measurements of  $\sigma_W$ ,  $\sigma_Z$  and  $M_W$ , and performing other tests of the electroweak theory, such events will be quite useful for calibration and alignment of the detector [12]. Once the detector is well understood, the study at the

LHC of diboson production will become interesting to search for the Higgs boson and for deviations from the Standard Model.

**3.2. Top quark physics.** – The top quark, discovered thirteen years ago at the Tevatron, is the heaviest quark and, for this reason, it plays an important role in loop corrections to several electroweak observables. Indeed, together with the accurate measurement of the  $W$  mass, the top-mass measurement constrains the mass of the Higgs boson.

The measurement of the top quark mass with the highest precision is one of the major goals of CDF and DØ. These two experiments already managed to measure the mass with a (combined)  $1.4 \text{ GeV}/c^2$  precision, exceeding past expectations [13]. The goal now is to reach a precision smaller than  $1 \text{ GeV}/c^2$ , before the Tevatron definitive turn-off.

As for the production cross section, the uncertainty reached by CDF and DØ is of the order of 10% (per experiment) and comparable to the theoretical uncertainties, thus enabling a test of NLO/NLL predictions.

Electroweak production of single top has a cross section about  $1/3$  of  $t\bar{t}$  pair production. Therefore, it has been more difficult to find evidence for it and to measure the single-top cross section, which gives also a direct measurement of the Cabibbo–Kobayashi–Maskawa matrix element  $V_{tb}$ .

In addition to mass and cross sections, other top properties are measured, such as its charge, lifetime, decay branching ratios and the  $W$  helicity in top decays  $t \rightarrow bW$ . Also, due to its large mass, top quarks might couple to New Physics at high energy scales and act as probes for these processes. For this reason, exotic decays or production mechanisms have been explored, but there is so far no evidence of heavy resonances or fourth-generation quarks.

The measurement at the LHC of the top quark properties will reach high statistical accuracy, given the large yield expected for top events. Precise measurements will require, however, a detailed modelling of the detector response, along with a good understanding of the sources of systematic uncertainty. Top events themselves can be used, through *in-situ* calibration of the jet energy scale, to help reduce such uncertainties [14].

**3.3. Standard Model Higgs.** – The measurements of  $W$  and top masses, together with other precision electroweak measurements, lead to the limit for the Standard Model Higgs-boson mass of  $86^{+36}_{-27} \text{ GeV}/c^2$  (see Figure 2), with a 95% C.L. upper limit of  $160 \text{ GeV}/c^2$ . If one also includes the results from direct searches at LEP, yielding  $m_H > 114 \text{ GeV}/c^2$ , the 95% C.L. limit becomes  $190 \text{ GeV}/c^2$ .

Such a (relatively low) expected mass sets Higgs-boson production possibly within reach of the Tevatron experiments, but, at the same time, the smallness of the production cross section makes it very hard to search for its evidence. This challenging task requires the experiments to aim at high sensitivity by combining all possible channels, improving efficiencies and reducing systematic uncertainties. Specific strategies need to be implemented for a low mass Higgs ( $m_H < 135 \text{ GeV}/c^2$ ), where the associated production ( $WH$  or  $ZH$ ) has the best chances, and for a (relatively) high mass ( $135 \div 200 \text{ GeV}/c^2$ ), where the channels  $H \rightarrow WW$  are the most favourable ones.

The CDF+DØ sensitivity reaches its optimum around  $160 \text{ GeV}/c^2$  where they could be able to reach some results before the Tevatron turn-off either in terms of exclusion or of evidence [16].

As for CMS and ATLAS, once the detector is well calibrated and its response known, they are expected to be sensitive to the discovery already with  $\approx 1 \text{ fb}^{-1}$  of data, if the Higgs mass is above  $140 \text{ GeV}/c^2$ , in the decay channels  $H \rightarrow ZZ$  and  $H \rightarrow WW$ .

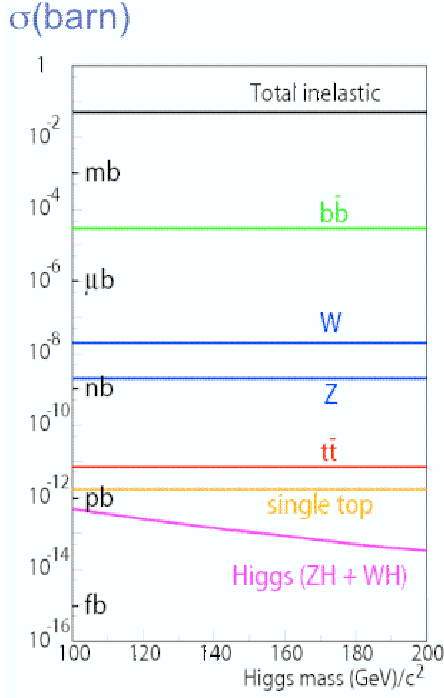


Fig. 1. – Production cross section at the Tevatron, as a function of the Higgs boson mass, for various processes.

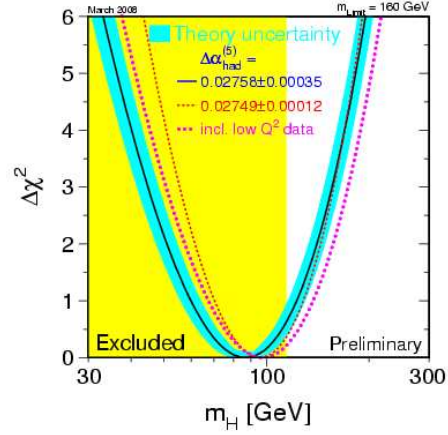


Fig. 2. – March 2008  $\Delta\chi^2$  curve derived from high- $Q^2$  precision electroweak measurements, performed at LEP and by SLD, CDF, and DØ, as a function of the Higgs boson mass, assuming the Standard Model. The yellow band on the left-hand side refers to the LEP2 direct search limit. From [15].

For lower Higgs masses, more luminosity, about  $5\text{--}10\text{ fb}^{-1}$ , will be needed and several channels will have to be included, in order to be sensitive to its observation [17].

**3.4. New Physics beyond the Standard Model.** – As discussed in section 2, many extensions of the Standard Model are introduced in order to address open issues, such as the hierarchy problem, or to provide different mechanisms of symmetry breaking or unify the fundamental forces.

The searches currently performed at the Tevatron are either inspired by a specific model or instead based on a specific signature. Searches for supersymmetric particles, new gauge bosons, extra dimensions, leptoquarks or Higgs compositeness belong to the first case. As for the second case, anomalous production of leptons, bosons and photons, as well as missing  $E_T$ , have been searched. No signal of supersymmetry, exotic particles or anomalous production has yet been found at the Tevatron and limits (more or less stringent, depending on the cases) have been set [18].

New Physics is searched also at HERA where, for instance, limits on contact interactions have been set [19].

Given the large luminosity that will be integrated, the LHC experiments will have the potential for important discoveries, either within the SUSY framework [20] or in other scenarios beyond the Standard Model [21]. Statistical uncertainties will not be a problem in most cases, but it will be crucial to understand the systematics in order to be able to

find evidence of new signals.

#### 4. – Conclusions

In this summary we have briefly reviewed the current status of the Standard Model of strong and electroweak interactions and underlined some of its drawbacks. We discussed improvements in the theory and their applications to collider phenomenology, as well as the most recent measurements carried out at present colliders, mostly at the Tevatron accelerator, and commented on the features of future measurements which will be carried out at the LHC.

On the theory side, QCD stands as a robust theory, which continuously yields predictions which are confirmed very well by the experiments. Nevertheless, more accurate perturbative calculations and a better understanding and modelling of its non-perturbative aspects are still of great interests, in order to fully control the backgrounds for many New Physics searches.

As for the electroweak interactions, the ultimate confirmation of the Standard Model awaits the discovery of the Higgs boson: as discussed, the LHC should be able to give a final answer to this point. Moreover, the absence of any Higgs signal so far, along with the open problems of the Standard Model, has pushed the development of a few new ideas on the electroweak symmetry breaking, which are theoretically well formulated and not in contradiction with the available electroweak precision tests. As only experimental measurements, *e.g.* the  $WW$  scattering cross section, can help to verify or disprove such models, we can just eagerly await for the next start of the LHC.

#### REFERENCES

- [1] OSSOLA G., these proceedings.
- [2] BOZZI G., these proceedings.
- [3] FERRERA G., these proceedings.
- [4] MAGNEA L., these proceedings.
- [5] NICOTRI S., these proceedings.
- [6] MIRABELLA E., these proceedings.
- [7] GUZZI M., these proceedings.
- [8] FRANCESCHINI R., these proceedings.
- [9] ACCOMANDO E., these proceedings.
- [10] BEVILACQUA G., these proceedings.
- [11] CAVALIERE V., these proceedings.
- [12] ROVELLI C., these proceedings.
- [13] GRESELE A., these proceedings.
- [14] COBAL M., these proceedings.
- [15] THE LEP ELECTROWEAK WORKING GROUP, <http://lepewwg.web.cern.ch/LEPEWWG/>.
- [16] MARGAROLI F., these proceedings.
- [17] SOLFAROLI E., these proceedings.
- [18] MANCA G., these proceedings.
- [19] BINDI M., these proceedings.
- [20] DE SANCTIS U., these proceedings.
- [21] BERNARDINI J., these proceedings.